

Volume 222, number 1, 83–88

FEB 05100

September 1987

# Amino acid sequence of a 32-residue region around the thiol ester site in duck ovostatin

Hideaki Nagase and Keith Brew\*

*Department of Biochemistry, University of Kansas Medical Center, Kansas City, KS 66103 and \*Department of Biochemistry, University of Miami School of Medicine, Miami, FL 33101, USA*

Received 9 July 1987

To obtain the amino acid sequence at the thiol ester site in duck ovostatin for comparisons with other proteins, the native ovostatin was labeled with  $^{14}\text{CH}_3\text{NH}_2$  at the reactive thiol ester site. The modified protein was reduced, carboxymethylated, and digested with trypsin.  $^{14}\text{C}$ -labeled peptides isolated by gel filtration with Sephadex G-50, ion-exchange chromatography on DEAE-cellulose and HPLC were subjected to automated sequence analysis, and the stretch of 32 amino acid residues containing the  $^{14}\text{CH}_3\text{NH}_2$ -binding site were determined. A comparison of this sequence with the corresponding sequences in  $\alpha_2$ -macroglobulin, and complement components C3 and C4 revealed 72, 31 and 34% homology, respectively. The results indicate that ovostatin is a close relative to plasma  $\alpha$ -macroglobulins and may share a common ancestor with C3 and C4.

Ovostatin;  $\alpha_2$ -Macroglobulin; Thiol ester; Amino acid sequence

## 1. INTRODUCTION

Ovostatin (ovomacroglobulin) is a tetrameric glycoprotein proteinase inhibitor synthesized specifically in avian [1–3] and reptilian [4] oviduct. The native molecule ( $M_r$  780 000) consists of four identical subunits ( $M_r$  195 000) which are linked in pairs by disulfide bonds [3]. The binding of a proteinase to ovostatin is initiated by proteolysis of a specific region of a subunit. This event triggers a conformational change in ovostatin resulting in the entrapment of the enzyme molecule without blocking the active site [5]. Thus, inhibition of proteinases is observed only when high- $M_r$  substrates are used. These observations indicate that the quaternary structure and the mechanism of proteinase inhibition by ovostatin are similar to those of the plasma glycoprotein,  $\alpha_2$ -macroglobulin

( $\alpha_2\text{M}$ ) [5,6]. Indeed, the  $\text{NH}_2$ -terminal sequences of ovostatin and  $\alpha_2\text{M}$  are sufficiently similar (about 36% identical in their first 14 residues) to suggest that the structural genes for ovostatin and  $\alpha_2\text{M}$  may have evolved from a common ancestor [3,7,8]. In spite of their similarities, evolutionary divergence has resulted in differences in specificities and chemical properties. Chicken ovostatin inhibits only metalloproteinases stoichiometrically [5] and duck ovostatin inhibits metalloproteinases and serine proteinases but not cysteine proteinases [7], whereas  $\alpha_2\text{M}$  can bind and inhibit almost all endopeptidases from four major classes of proteinases [6]. In addition, the most striking difference found between chicken ovostatin and  $\alpha_2\text{M}$  is that chicken ovostatin lacks a reactive thiol ester [5]. As a result, chicken ovostatin, unlike  $\alpha_2\text{M}$ , does not form a covalent linkage with the entrapped proteinase. Although the example of chicken ovostatin demonstrates that the thiol ester moiety is not essential for proteinases inhibition by this family of proteins, thiol esters have been found in all  $\alpha$ -macroglobulins in

Correspondence address: H. Nagase, Department of Biochemistry, University of Kansas Medical Center, 39th and Rainbow Blvd, Kansas City, KS 66103, USA

plasma from various species reported so far [3,9–13].

More recently, however, we have reported that such a thiol ester is present in duck ovostatin [7]. Thiol esters have also been found in complement components C3 [14–16] and C4 [17,18], and similarities in sequence around this region in  $\alpha_2$ M and C3 and C4 have suggested that they share a common evolutionary origin [19,20].

In order to locate an internal thiol ester in duck ovostatin and to examine its structural relationship with  $\alpha_2$ M, C3 and C4, we have sequenced 32 amino acid residues around the thiol ester site in duck ovostatin. The sequence analysis displays a high degree of similarity with the corresponding sequences of  $\alpha_2$ M and to a lesser extent with those of C3 and C4. The results further support the hypothesis that parts of the structural genes for ovostatin,  $\alpha_2$ M, C3 and C4, have arisen from a common ancestor.

## 2. MATERIALS AND METHODS

### 2.1. Materials

Duck ovostatin was purified as described [7].  $^{14}\text{CH}_3\text{NH}_2 \cdot \text{HCl}$  (spec. act. 56 mCi/mmol) was from Amersham.  $\text{CH}_3\text{NH}_2 \cdot \text{HCl}$ , dithiothreitol, iodoacetic acid and TPCK-treated trypsin were from Sigma. Sephadex G-50 (superfine) and DE-52 were from Pharmacia and Whatman, respectively.

### 2.2. $^{14}\text{CH}_3\text{NH}_2$ labeling of duck ovostatin

Labeling of duck ovostatin with  $^{14}\text{CH}_3\text{NH}_2$  was first carried out by reacting 225  $\mu\text{l}$  ovostatin (10.6 mg/ml) with 90  $\mu\text{l}$  of 175 mM  $^{14}\text{CH}_3\text{NH}_2$  (10 mCi/ml) in 0.1 M boric acid/NaOH, pH 8.6, containing 0.2 M NaCl. The final concentration of  $^{14}\text{CH}_3\text{NH}_2$  was 50 mM, conditions under which the labeling reaction proceeds efficiently. After a 4 h reaction at 37°C, 1 ml duck ovostatin (10.6 mg/ml) was added to the mixture and it was further incubated at 37°C for 4 h. The sample was then mixed with 24 ml duck ovostatin (10.6 mg/ml) in 0.1 M boric acid/NaOH, pH 8.6, containing 0.2 M NaCl, incubated at 37°C for 1 h. The sample was then treated with 0.2 M  $\text{CH}_3\text{NH}_2$  for 16 h at room temperature in order to obtain a chemically uniform product.

### 2.3. Tryptic digestion of duck ovostatin

$^{14}\text{CH}_3\text{NH}_2$ -labeled ovostatin was dialyzed against 50 mM  $\text{NH}_4\text{HCO}_3$ , lyophilized, dissolved in 35 ml of 0.1 M Tris-HCl, pH 8.6/8 M urea, reduced with 10 mM dithiothreitol at 37°C for 4 h and alkylated with 30 mM iodoacetic acid. Reduced, carboxymethylated  $^{14}\text{CH}_3\text{NH}_2$ -labeled ovostatin was dialyzed against 50 mM  $\text{NH}_4\text{HCO}_3$ , lyophilized, and digested with 5 mg TPCK-trypsin in 20 ml of 50 mM  $\text{NH}_4\text{HCO}_3$  containing 1 mM  $\text{CaCl}_2$  for 2 h at 37°C, then with an additional 5 mg TPCK-trypsin for 2 h. Insoluble peptides generated were separated by centrifugation. More than 90% of the radioactivity was recovered in the supernatant. The tryptic fragments containing radioactivity were purified by a series of chromatographic techniques (see section 3). CNBr cleavage was carried out with a 2% (w/v) solution of CNBr in 70% formic acid for 18 h at 20°C.

### 2.4. Amino acid analysis

Peptides were hydrolyzed with 6 N HCl at 110°C for 24 h and amino acid compositions determined by conversion to PTC derivatives and analysis by HPLC. Hydrolysis and conversion was carried out with a Waters Pico Tag workstation, and analysis with a Waters Pico Tag HPLC column, following the procedures suggested by the manufacturer.

### 2.5. Sequence analysis

Automatic sequence analyses were performed with an Applied Biosystems 470A protein sequencer using standard programs. PTH-amino acids were identified and quantified by reverse-phase HPLC using a Hewlett Packard 1090 liquid chromatograph with an Applied Biosystems narrow bore (2.1  $\times$  220 mm) PTH-C18 cartridge system. HPLC solvents were supplied by Applied Biosystems, and elution was carried out following their recommendations.

## 3. RESULTS AND DISCUSSION

### 3.1. Isolation of $^{14}\text{CH}_3\text{NH}_2$ -labeled peptides

$^{14}\text{C}$ -labeled peptides generated by TPCK-treated trypsin digestion were separated first with a column of Sephadex G-50 superfine (4.5  $\times$  55 cm), equilibrated and eluted with 50 mM  $\text{NH}_4\text{HCO}_3$ . Three radioactive peaks were detected but only the

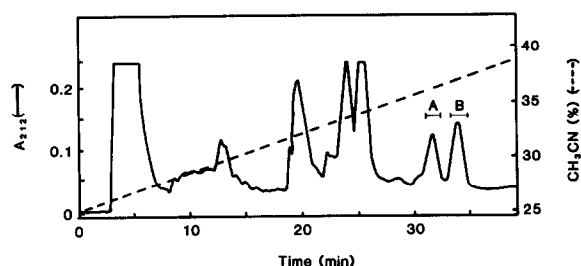


Fig. 1. Separation of two  $^{14}\text{C}$ -labeled peptides by reverse-phase HPLC.  $^{14}\text{C}$ -labeled peptides obtained after DE-52 chromatography were dissolved in 2 ml of 6 M guanidine·HCl/15% formic acid, and 400  $\mu\text{l}$  of the sample was applied to a reverse-phase C-18 column (Vydac) equilibrated with 0.1% trifluoroacetic acid. The peptides were eluted with a linear gradient at a flow rate of 1 ml/min. Each peak of  $A_{212}$  was collected and measured for radioactivity. Peaks A and B had 40 and 60% of the total radioactivity, respectively.

fractions containing the major peak were pooled, lyophilized, and subjected to further purification. The lyophilized material from the Sephadex G-50 column was dissolved in 10 mM  $\text{NH}_4\text{HCO}_3$  and applied to a column of DE-52 ( $2 \times 20$  cm) equilibrated with the same solvent. The  $^{14}\text{C}$ -labeled peptides bound to DE-52 and were eluted with a gradient of  $\text{NH}_4\text{HCO}_3$ . The majority of the  $^{14}\text{C}$  label appeared in one major peak. The pool from DE-52 was lyophilized and dissolved in 2 ml of 6 M guanidine·HCl/15% formic acid. The fraction was further purified by HPLC (Bio Rad MAPS system) with a reverse-phase column (Vydac C18 protein and peptide column) using a gradient of 25–60% acetonitrile containing 0.1% trifluoroacetic acid (fig.1). The  $^{14}\text{C}$  label was found in two peaks (peak A with 40% and peak B with 60% of the total radioactivity).

Table 1  
Sequence of  $^{14}\text{CH}_3\text{NH}_2$ -labeled peptides of duck ovostatin

Cycle	Peptide A		Peptide B		Peptide A-3		
	Residue	Yield	Residue	Yield	Residue	Yield	cpm
1	Ser	112	Ala	1195	Pro	232	64
2	Val	318	Ser	380	Phe	234	40
3	Val	490	Phe	435	Gly	173	262
4	Gly	270	Ser	190	Cm-Cys	98	202
5	Asp	203	Val	490	Gly	148	240
6	Ile	324	Val	385	Glu	127	208
7	Met	230	Gly	260	$^{14}\text{CH}_3\text{NH-Glu}$	103	1375
8	Gly	202	Asp	180	Asn	46	1050
9	Thr	68			Met	N.D.	180
10	Ser	65					
11	Met	238					
12	Gln	195					
13	Asn	156					
14	Leu	290					
15	His	62					
16	Gln	124					
17	Leu	177					
18	Leu	246					
19	Gln	104					
20	Met	108					
21	Pro	99					
22	Phe	104					
23	Gly	81					
24	Cm-Cys	32					

Yields at each cycle are given in pmol. N.D., not determined

Table 2  
Amino acid composition of peptides A, B, and A-3

	Peptide A	Peptide B	Peptide A-3
Asp	3.44 (3)	6.13 (6)	0.88 (1)
Glu	5.90 (5)	9.80 (10)	2.02 (2)
Cm-Cys	N.I. (1)	1.07 (1)	0.72 (1)
Ser	2.5 (3)	5.4 (5)	
Gly	4.07 (4)	6.9 (7)	2.30 (2)
His	0.97 (1)	1.6 (2)	
Arg			
Thr	1.7 (1)	2.55 (3)	
Ala		2.28 (2)	
Pro	0.87 (1)	1.75 (2)	0.89 (1)
Tyr	N.D.	N.D.	
Val	2.32 (2)	3.43 (3)	
Met	3.9 (4)	4.15 (4)	N.I. (1)
Ile	1.28 (1)	2.08 (2)	
Leu	2.74 (3)	5.45 (5)	
Phe	1.47 (2)	3.70 (4)	0.94 (1)
Lys		0.60 (1)	

N.I., not identified; N.D., not determined

### 3.2. Sequence analyses of peptide A and peptide B

From four separate runs of HPLC as shown in fig.1, the pools of peptides A and B were combined separately, dried under vacuum, and one-fifth of each peptide was used for analyses of sequence (table 1) and amino acid composition (table 2). The sequence obtained for the first 24 residues of peptide A appeared to correspond to residues 926–949 in human  $\alpha_2$ M [8]. Cm-Cys identified in cycle 24 was possibly the Cys residue which is generated from the cleavage of the thiol ester bond between Cys and Glx analogously to  $\alpha_2$ M [21–23]. One SH group is generated from each ovostatin subunit after treating the native duck ovostatin with  $\text{CH}_3\text{NH}_2$  [7]. Peptide B showed an identical sequence to that of peptide A, but with three additional residues (Ala-Ser-Phe) at the amino-terminus of peptide A (table 1). Peptide B was probably generated by normal tryptic cleavage of duck ovostatin since in  $\alpha_2$ M, the residue preceding this region is Arg [8], and peptide A was generated by cleavage at the Phe–Ser bond as a result of residual chymotryptic activity in the trypsin preparation. Indeed, the amino acid composition of peptide B revealed one residue of Lys, and peptide A appeared to be considerably shorter than peptide B (table 2).

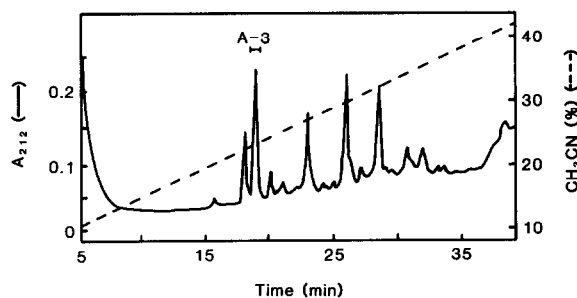
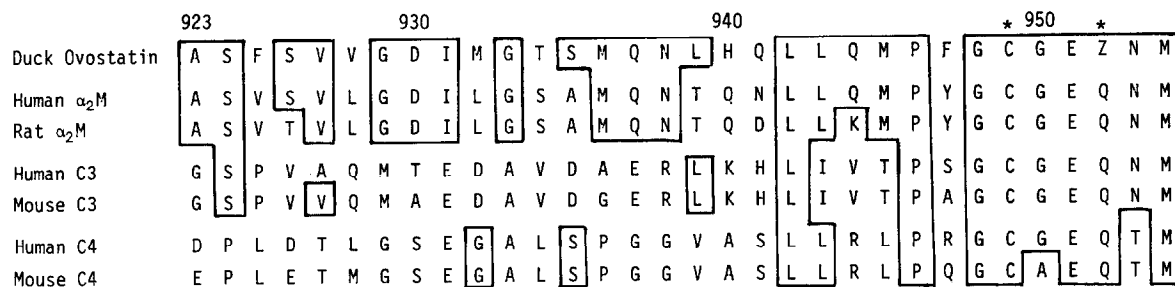


Fig.2. Separation of CNBr fragments of peptide A by reverse-phase HPLC. Peptide A was reacted with 200  $\mu$ l of a 2% (w/v) solution of CNBr in 70% formic acid at 23°C for 18 h. After drying in vacuo over NaOH pellets, the products were dissolved in 6 M guanidine·HCl and applied to a reverse-phase C18 column (Vydac) attached to an HPLC system (Bio-Rad MAPS). The peptides were eluted with the linear gradient of acetonitrile at a flow rate of 1 ml/min. Each peak of  $A_{212}$  was collected and measured for radioactivity.  $^{14}\text{C}$  label was found in peak A-3.

To determine a more extended sequence around the thiol ester site of duck ovostatin, the remaining peptide A was cleaved with CNBr and the fragments generated were separated by HPLC with a reverse-phase C-18 column (fig.2).  $^{14}\text{C}$  label was only found in peptide A-3. Sequence analysis of A-3 showed that the peptide was generated by cleavage of the Met-Pro between residues 20 and 21 of peptide A (table 1). After each Edman degradation cycle of peptide A-3, the amount of  $^{14}\text{C}$  label recovered in the PTH derivative was measured to identify the site of  $^{14}\text{CH}_3\text{NH}_2$  incorporation. Radioactivity was recovered in cycle 7 and to a lesser extent in cycle 8 (table 1), indicating that  $^{14}\text{CH}_3\text{NH}_2$  was covalently linked to residue 7 of peptide A-3. Identification of this residue as Glx was deduced from the amino acid composition of peptide A-3 (table 2) and by the presence of a PTH derivative that eluted at a distinct position from those of normal amino acids together with some PTH-Glu resulting from the cleavage of the methylamine moiety during the conversion of anilinothiazoline to a PTH derivative.

### 3.3. Comparison of the sequences around the thiol ester sites of ovostatin, $\alpha_2$ M, C3 and C4

At present, it appears that reactive inter-chain  $\beta$ -cysteinyl- $\gamma$ -glutamyl thiol esters are uniquely found in complement components C3 and C4 and



chicken ovostatin, have  $\text{CH}_3\text{NH}_2$ -sensitive sites, presumably reflecting the presence of thiol esters. To understand the evolutionary and functional relationship of this family of proteins, we are currently investigating the sequence in chicken ovostatin which corresponds to the thiol ester sites of other members of this family using molecular cloning techniques.

#### ACKNOWLEDGEMENTS

This work was supported by National Institutes of Health grants HD 18796 and GM 21363 and a Biomedical Research Support Grant from the University of Kansas Medical Center.

#### REFERENCES

- [1] Miller, H.T. and Feeney, R.E. (1966) *Biochemistry* 6, 952–958.
- [2] Kitamoto, T., Nakashima, M. and Ikai, A. (1982) *J. Biochem. (Tokyo)* 92, 1679–1682.
- [3] Nagase, H., Harris, E.D. jr, Woessner, J.F. jr and Brew, K. (1983) *J. Biol. Chem.* 258, 7481–7489.
- [4] Ikai, A., Kitamoto, T. and Nishigai, M. (1983) *J. Biochem. (Tokyo)* 93, 121–127.
- [5] Nagase, H. and Harris, E.D. jr (1983) *J. Biol. Chem.* 258, 7490–7498.
- [6] Starkey, P.M. and Barrett, A.J. (1977) in: *Proteinases in Mammalian Cells and Tissues* (Barrett, A.J. ed.) pp.663–696, Elsevier/North-Holland, Amsterdam, New York.
- [7] Nagase, H., Harris, E.D. jr and Brew, K. (1986) *J. Biol. Chem.* 261, 1421–1426.
- [8] Sottrup-Jensen, L., Stepanik, T.M., Kristensen, T.E., Wierzbicki, D.M., Jones, C.M., Lönblad, P.B., Magnusson, S. and Peterson, T.E. (1984) *J. Biol. Chem.* 259, 8318–8327.
- [9] Barrett, A.J. (1981) *Methods Enzymol.* 80, 737–754.
- [10] Björk, I., Lindblom, T. and Lindahl, P. (1985) *Biochemistry* 24, 2653–2660.
- [11] Gonias, S.G., Balber, A.E., Hubbard, W.J. and Pizzo, S.V. (1983) *Biochem. J.* 209, 99–105.
- [12] Feldman, S.R. and Pizzo, S.V. (1985) *Biochemistry* 24, 2569–2575.
- [13] Starkey, P.M. and Barrett, A.J. (1982) *Biochem. J.* 205, 105–115.
- [14] Howard, J.B. (1980) *J. Biol. Chem.* 255, 7082–7084.
- [15] Tack, B.F., Harrison, R.A., Jonatova, J., Thomas, M.G. and Prahl, J.W. (1980) *Proc. Natl. Acad. Sci. USA* 77, 5764–5768.
- [16] Pangburn, M.K. and Müller-Eberhard, H.J. (1980) *J. Exp. Med.* 152, 1102–1114.
- [17] Campbell, R.D., Gagnon, J. and Porter, R.R. (1981) *Biochem. J.* 199, 359–370.
- [18] Harrison, R.A., Thomas, M.L. and Tack, B.F. (1981) *Proc. Natl. Acad. Sci. USA* 78, 7388–7392.
- [19] Sim, R.B. and Sim, E. (1981) *Biochem. J.* 193, 129–141.
- [20] Sottrup-Jensen, L., Stepanik, T.M., Kristensen, T., Lönblad, P.B., Jones, C.M., Wierzbicki, D.M., Magnusson, S., Domdey, H., Wetsel, R.A., Lundwall, A., Tack, B.F. and Fey, G.H. (1985) *Proc. Natl. Acad. Sci. USA* 82, 9–13.
- [21] Howard, J.B. (1981) *Proc. Natl. Acad. Sci. USA* 78, 2235–2239.
- [22] Sottrup-Jensen, L., Hansen, H.F., Mortensen, S.B., Peterson, T.E. and Magnusson, S. (1981) *FEBS Lett.* 123, 145–148.
- [23] Salvesen, G.S., Sayers, C.A. and Barrett, A.J. (1981) *Biochem. J.* 195, 453–461.
- [24] Sand, O., Folkersen, J., Westergaard, J.G. and Sottrup-Jensen, L. (1985) *J. Biol. Chem.* 260, 15723–15735.
- [25] Saito, A. and Sinohara, H. (1985) *J. Biol. Chem.* 260, 775–781.
- [26] Esnard, F., Gutman, N., Moujahed, E. and Gauthier, F. (1985) *FEBS Lett.* 182, 125–129.
- [27] Quigley, J.P. and Armstrong, P.B. (1983) *J. Biol. Chem.* 258, 7903–7906.
- [28] Tack, B.F. (1983) *Springer Semin. Immunopathol.* 6, 259–282.
- [29] Arakawa, H., Osada, T. and Ikai, A. (1986) *Arch. Biochem. Biophys.* 244, 447–453.
- [30] Harpel, P., Hayes, M.B. and Hugli, T.E. (1979) *J. Biol. Chem.* 254, 8669–8678.
- [31] Sepkoski, J.J. (1978) *Paleobiology* 4, 223–251.
- [32] Gehring, M.R., Shiels, B.R., Northemann, W., DeBruihn, M.H.L., Kan, C.-C., Chain, A.C., Noonan, D.J. and Fey, G.H. (1987) *J. Biol. Chem.* 262, 446–454.
- [33] DeBruihn, M.H.L. and Fey, G.H. (1985) *Proc. Natl. Acad. Sci. USA* 82, 708–712.
- [34] Wetsel, R.A., Lundwall, Å., Davidson, F., Gibson, T., Tack, B.F. and Fey, G.H. (1984) *J. Biol. Chem.* 259, 13857–13862.
- [35] Belt, K.T., Carroll, M.C. and Porter, R.R. (1984) *Cell* 36, 907–914.
- [36] Nonaka, M., Nakayama, K., Yeul, Y.D. and Takahashi, M. (1985) *J. Biol. Chem.* 260, 10936–10943.